THE MORPHOLOGY OF LOW SURFACE BRIGHTNESS DISK GALAXIES

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ABSTRACT

We present $UBVI$ and $H\alpha$ images of a sample of Low Surface Brightness (LSB) disk galaxies. These galaxies are generally late types, if they can be sensibly classified at all. However, they not dwarfs, being intrinsicly large and luminous. The morphology of LSB galaxies is discussed in terms of the physical interpretation of the Hubble sequence, the stages of which are found to be nonlinear in the sense that smaller physical differences separate mid to early type spirals than late types. The morphological similarity of LSB disks to faint galaxies resolved by *HST* is noted, as are several apparently young galaxies.

1. INTRODUCTION

Morphological classification of galaxies represents the earliest form of extragalactic astronomy. Detector technology initially allowed only galaxies of high contrast with respect to the sky background to be catalogued and classified. Selection effects have the potential to be severe in this case. However, in the last few years, a large number of low contrast or Low Surface Brightness (LSB) galaxies have been discovered and cat aloged (Schombert & Bothun 1988; Schombert et al. 1992; Impey et al. 1994). In general, LSB galaxies span the same range of physical parameters as galaxies which occupy the conventional Hubble sequence; they are not exclusively low mass dwarf galaxies, Since LSB galaxies are defined as having central sut'face brightnesses fainter than the darkest night sky, an investigation of their morphological properties may reveal if they form some kind of hidden Hubble sequence. Previous work has firmly established that the physical properties of LSB galaxies are strikingly different from those of the high surface brightness (HSB) spirals which define the Hubble sequence (McGaugh 1992). These differences may provide important clues to the physics underlying morphology.

Morphological classification of galaxies has traditional been dcmc by visual inspection of galaxy images on B-band photographic plates. This intrinsically non-linear process is difficult to duplicate using linear, digital CCDs. As such, morphological classification may be more! difficult and less precise in the digital era (see discussion in van den Bergh, Pierce, & Tully 1990). To assist in the morphological classification of LSB galaxies, in this paper we present images in U, B, V, I, and $H\alpha$ of 22 LSB galaxies. This is not a complete sample in any sense, but dots represent the lowest surface brightnesses disk galaxies that can be extracted from diameter limited field surveys using visual inspection of plate material (e.g., the UGC, Nilson 1973; and the POSS-II LSB list, Schombert et al. 1992). This population of galaxies is very different from "normal" HSB field spirals and LSB dwarfs in clusters (e.g., Impey, Bothun, & Malin 1988; Irwin et al. 1990; Bothun, Impey, & Malin 1991).

In §2 we discuss the morphology of this sample of LSB galaxies, note their similarity to the excess population of faint blue galaxies, and investigate the implications that the physical properties of these galaxies have for the interpretation of the Hubble sequence. We comment on the CCD images of interesting individual LSB galaxies in §3, some of which are potentially young galaxies. Our results are brifly summarized in §4. Throughout the paper, all distance dependent quantities assume $H_0 = 100h$ km s^{-1} Mpc^{-1} and a Virgo infall velocity of 300 km s^{-1}.

2. MORPHOLOGY

2.1 *LSB Galaxies*

In general, LSB galaxies are late type (Sc and later) spiral and irregular galaxies. The spiral pattern is often incipient or fragmentary and usually faint and difficult to trace (e.g., F530-3, F558-1, F561-1, F568-1, F568-6, F577-V1, UGC 1230, UGC 5709, UGC 6151, UGC 6614, and UGC 9024). The low visibility of the spiral pattern and frequently irregular or amorphous appearance of the disk often result in a dwarf classification, though few of the galaxies discussed here are actually faint enough to formally qualify as such ($M > -16$). Galaxies which do include F415-3 and F611-1, but, for instance, UGC 12695 is twice the size of the Milky Way. Bulge components arc faint or totally undetectable in most cases (e.g., F561-1, UGC 1230, and UGC 6151), but in a significant subset the bulges are bright, These bulges generally have effective radii of 2-3 kpc and arc of normal surface brightness. If anything, there is a tendency for the LSB galaxies with prominent bulges to have larger, lower surface brightness disks than the more typical bulgeless LSB galaxies (e.g., F530-3, F568-6, UGC 9024, and especially UGC 6614). Bars are very rare, at least in this B-selected sample. As most bars arc dynamical tracers of a previous tidal interaction, their paucity in this sample may be another indication of isolation on small scales (see also Bothun et al. 1993), !l'here arc sometimes lens components in the surface brightness profiles, but it is more common for the profile to be simply exponential with some noise.

The original Hubble sequence ended with type Sc (Hubble 1936). This particular stage encompasses a very wide range of intrinsic galaxy properties, including many LSB galaxies. In fact, most of the highest, surface brightness disks which are known (e.g., M1OI) arc Sc galaxies. Still, it became necessary to extend the Hubble sequence to ever later types as progressively better plate material was examined. Interestingly, prior to LSB galaxies being so named, they were predominant members of the new Hubble type, Sd. An excellent nearby example of this is provided by NGC 247. The majority of LSB galaxies fall in the late type bins of this classification] scheme (to the extent that they do at all), as might be expected from the nature of the selection effects which act against them (Allen & Shu 1979; McGaugh 1995),

2.2 *Faint Blue Galaxies* ?

As the limits of observation have been pressed ever deeper, a large excess in the numbers counts of galaxies at faint magnitudes has been noted (Tyson 1988; Lilly, Cowie, & Gardner 1991; Colless et al, 1991), McGaugh (1994a) and Ferguson & McGaugh (1.994) argued that this could be at least in part duc to surface brightness selection effects which act preferentially against LSB galaxies locally. Recently, Griffiths et al. (1994) and Glazebrook et al. (1994) have resolved galaxies in the magnitude range of the excess with *HST*. They find that the excess is duc to peculiar, irregular looking galaxies, many of which do not fit into the traditional classification scheme, In addition, the data set of Wirth, Koo, & Kron (1994) on CL0016+16 reveals a significant difference in light concentration index ratio as a function of g-r color: the blue galaxies tend 1)e the ones with the lowest light concentration indices.

This new morphlogical information provided by the HST observations is consistent with the scenario suggested by McGaugh (1 994a), namely, that the $z =$ O population of LSB disk galaxies have global properties quite similar to the faint blue galaxy population. Indeed, the simulated *HST* images of Ferguson & McGaugh (1994) predict an excess of edge-on, fuzzy, and irregular objects over what is expected from models based on standard galaxy mixes lacking LSB galaxies. '1'bough the simulations arc intentionally extreme, they bear a greater morphological resemblance to actual *HST* data than dots the standard no evolution model, indicating that the nearby objects discussed here may be very similar to what has been considered an engimatic population of faint blue galaxies. If the local population of LS13 galaxies do indeed correspond to that responsible for the excess counts at faint magnitudes, then the redshift distribution of the galaxies classified as peculiar by Glazebrook et al. (1994) should be skewed towards somewhat lower redshift than the normal populations in the same magnitude range. However, the degree Of the skew depends on the precise form of the bivariate distribution and the true slope of the faint end of the luminosity function (see Ferguson & McGaugh 1994).

2.3 *The Hubble Sequence*

The study of galaxies as physical objects is often expressed as an effort to understand the Hubble sequence. Being essentially a matter of appearance, as principally manifested by arm texture and definition, classification along the Hubble sequence of spirals is affected by the surface brightness of a galaxy through the contrast of its features relative to the background. A strong contrast facilitates perception of morphological distinctions, particularly when imaging with a non-linear detector. As a consequence, one might suspect that the Hubble sequence is also nonlinear in the sense that objects with high surface brightness would be more finely typed than others. This is analogous to stellar spectral typing, in which there is one nonlinear transformation from spectral type to the underlying physical variable of temperature (F stars covering a small range in temperature), then another from temperature to mass (O stars representing a very large linear mass range). These effects lead to an HR diagram which has obvious main sequence discontinuities when plotted in terms of spectral tpyes despite a presumably smooth underlying mass function (Houk & Cowley 1975).

For stars, at least, these effects are well understood. Such cannot be said of the Hubble sequence. The identification of the physical properties underlying it remains elusive. Quantifiable global properties are not well correlated with Hubble type (Boroson 1981; Kennicutt 1981; Bothun 1982; Kent 1985) and objective techniques seem to indicate that all characteristics of an image play a role in classification (Storri-Lombardi et al. 1992). Clearly it is necessary to sort out any nonlinearities in the classification scheme before such trends that do exist can be interpreted physically.

A basic problem, however, is that morphological classification is an inherently non-quantitative process. Despite the many quantitative measurements that can now be made for galaxies, morphological classification still persists as a substitute therefor. For instance, a fundamental property of galaxies which can be quantified is their luminosity profiles. For disk galaxies, these have the form

$$\mu(r) = \mu_0 + 1.086\frac{r}{\alpha}, \tag{1}$$

where μ_0 is the central surface brightness and α is the scale length of the disk. These characterize the luminosity density and the size of a galaxy, If morphological classification is to reflect underlying physics, then the least one should hope for is a positive correlation between measured galaxy structure and morphological type.

One complication is that the observed central surface brightness μ_0 needs to be inclination corrected to obtain the true face on value, μ_0^c. Usually this is done by assuming that the disks are optically thin, so that only edge brightening occurs. This is a dubious assumption, but we retain it for consistency with other published data as it is usually a small correction compared to the range of surface brightness considered here and hence makes no difference to the results. If anything, the assumption of no extinction is more appropriate in these LSB systems which are relatively dust free (McGaugh 1994b).

A link between μ_0^c and underlying physics was first suggested by Freeman (1970), who found that all spirals had $\mu_0^c = 21.65 \pm 0.3$ B mag arcsec^{-2}. If this were a true physical result, and not due to selection effects, improper bulge deconvolution, or disk galaxy opacity, then it would imply that the processes of galaxy formation conspired to always arrive at a particular mass surface density. However, as noted by Schombert et al. (1992), the very existence of disk galaxies with μ_0^c many standard deviations from the Freeman (1970) result indicates that the surface brightness distribution is not so sharply peaked. The LSB systems under consideration here fall far from the Freeman value, with typical inclination corrected central surface brightnesses of $\mu_0^c \approx 23.8$ B mag arcsec^{-2}. Other investigations (McGaugh 1993; McGaugh et al. 1994; de Jong & van der Kruit 1994; Sprayberry 1994; McGaugh 1995), demonstrate that the space density of LSB galaxies is in fact similar to that of Freeman disks. Moreover, the global properties of disk galaxies (e.g., color, rotation velocity, profile shape, H I content) seem to be largely independent of μ_0^c (McGaugh 1992).

Figure 1 shows the distribution of disk galaxies in the (μ_0^c, α) plane. Data are taken from van der Kruit (1987), Romanishin, Strom, & Strom (1983), and McGaugh & Bothun (1994). The data of McGaugh & Bothun (1994) are based on the images presented below. Intrinsically small ($\alpha < 1\ h^{-1}$ kpc) galaxies are excluded since we wish to discuss only those disk galaxies which are comparable in size to the spirals which define the Hubble sequence, As can be seem from Figure 1, the space density of galaxies as a function of μ_0^c is not simply a matter of size or morphological type, as argued by van der Kruit (1987).

Galaxies do not distinguish themselves much by Hubble type in this diagram (see also de Jong & van der Kruit 1994). There is a tendency for galaxies of low surface brightness to be classified as late types, but all Hubble types cover the same range in size. Things morphologically classed as dwarfs are not necessarily small (see also Schneider et al. 1992). Late types do tend to be less luminous owing to their lower surface brightness at a given size. Examples of very large, luminous LSB disks do exist; these tend to be labeled as relatively early types because of their prominent bulges and anemic spiral structure but probably represent a unique and distinct class of galaxies (Schombert et al. 1992; Sprayberry et al. 1994).

Note that disk absolute magnitudes generally do not exceed $M_B = -21$, and that this limit is approached by LSB as well as HSB galaxies. 'his result probably has the most to do with the physical conditions which are required to produce a spiral galaxy, perhaps indicating the maximum baryonic mass which has had time to cool. Another interesting feature in figure 1 is the apprent envelope demarcated by a line running from $\alpha = 3$ kpc at the faintest surface brightness plotted to $\alpha = 10$ kpc at the brightest. Though some giant LSB galaxies exist, there does seem to be a slight tendency for larger disks to be higher in surface brightness. This is suggestive of a bivariate distribution in which there is a modest correlation between size and surface brightness, and which has a sharp decline in the density of galaxies larger than the envelope. This is analogous to the knee of the luminosity function, but is not orthogonal to the surface brightness axis as usually assumed.

Unfortunately, it is not possible to say more than this from the present data, but if there is a real trend of this sort, then the slope of the faint end of the field luminosity function is likely to have been underestimated (McGaugh 1994a; Ferguson & McGaugh 1994).

Though the Hubble type is loosely related to surface brightness, it is interesting to note that the overlap between types is substantial. This is especially true for early type disks which predominantly occur at high surface brightnesses around the Freeman (1970) value. There is no distinction between S0, Sa, Sb, and to a lesser extent, Sc, galaxies in Figure 2. This of course means that other characteristics, such as arm texture, etc., play a dominant role in classification. Such details are much less striking in LSB galaxies in spite of the frequency of spiral structure. In fact, surface brightness should be considered as another dimension in a more proper 2-dimensional galaxy classification systems, such as the RDDO system initiated by van den Bergh (1976).

Being based largely on arm texture and the tightness of the wrapping of spiral arms, it is perhaps not surprising that the Hubble sequence does not distinguish μ_0^c and α which are the basic properties of disks. However, disks are not the only component of the luminosity profile, and another aspect which enters the morphological classification is the central concentration of the light, often quantified by the bulge to disk ratio B/D. Simien & de Vaucouleurs (1986) give a detailed formula relating morphological type to mean B/D. However, there is a great deal of scatter in B/D at a given type, much of which is real (Boroson 1981; Bothun 1982; Kent 1985). Low surface brightness galaxies pose particular difficulties in this regard because of their apparent bimodal distribution of bulge sizes. Most LSB galaxies have $B/D < 0.1$, but a significant subset have $B/D \sim 1$ with no obvious transition population. The classification of large bulge LSB spirals by arm texture can not be reconciled with that by B/D. Looking only at the arms, these are late types. But judging by B/D, they are early types.

This may just be a further indication that the Hubble sequence is less fundamental to the nature of galaxies as physical objects than might be hoped. The fact that early type spirals cluster strongly around the Freeman (1970) value, while later types cover a much larger area of this parameter space suggests that the high contrast of HSB galaxies allow for fine distinctions in appearance to be made between them. LSB galaxies are lumped into a few late type bins because it is difficult to see anything more about them other than that they are fuzzy blobs. Indeed, this is similar to Messier's objects which when initially discovered were all faint diffuse blobs, unclassifiable using the imaging capabilities of the time. Thus it appears that the Hubble sequence is indeed nonlinear, providing detailed information over a relatively small portion of the parameter space occupied by galaxies where the contrast is the best. There is therefore a tendency to infer big differences in type from small physical differences when the contrast is high, and little or no difference in type despite large physical differences when the contrast is poor.

This is amply clear in the football shaped classification diagram of de Vaucouleurs (1959), which places the most emphasis on early type spirals. While this is an accurate portrayal of the classification system, the *physical* parameter space continues to expand towards later types, which exhibit a wide and unusual range of properties. LSB galaxies alone cover a wide range in size as well as surface brightness, and also in color (McGaugh

& Bothun 1.994), metallicity (McGaugh 1994b), gas content and star formation properties (van der Hulst et al. 1987, McGaugh 1992; vail dcr Hulst et al. 1993). Considering that LSB galaxies arc actually quite common it is important to understand them as physical objects if we arc to decipher the meaning of the Hubble sequence.

By way of analogy, consider the case of stellar populations. When Baade (1944) first resolved stars in the bulge of the Andromeda galaxy, he was able to introduce the concept of stellar populations with the aid of the HR diagram for stars in our own galaxy as an interpretive tool. Even though only the 1)rightest stars were resolved, knowledge of the HR diagram allowed assignment of the red bulge stars to a population similar to that of globular clusters, while the bright blue stars of the disk belonged to a population similar to that of the solar neighborhood, However, the reverse is not possible -- without *a priori* knowledge of the HR diagram, one could never infer the existence of the main sequence from Baade's data. Although some attempts have been made (e.g., Whitmore 1984), there remains no physically understood equivalent of the HR diagram for galaxies. B y concentrating only on the most conspicuous exan iples of extragalactic stellar systems, we may be missing the analog of the main sequence for galaxies.

Though it has not succeeded as a tool for understanding galaxies the way the HR diagram has for stars, the Hubble sequence dots have. merit. Despite the large amount of real scatter, there is a clear trend of B/D with type. There arc large regions of parameter space which real galaxies do not occupy (e.g., there arc no giant HSB galaxies, cf. Kent 1985; Sprayberry et al. 1994; de Jong & van der Kruit 1994,), and though the scatter again is large, the boundaries do seem to be delineated by type. Given that there is always a great deal of scatter in plots involving morphological type, these uninhabited regions of parameter space may be telling us more about disk galaxy formation than any of the weak trends that do exist.

Since the Hubble sequence is essentially onc of regularity, with type varying from early type galaxies which arc smooth in appearance to irregular late types, perhaps the most important physical characteristic is the star formation time scale (cf. Kennicutt 1983). Most of the star formation in early type galaxies occurred long ago, so dynamical processes have had time to regularize the appearance of stochastic variations in bright star formation cites which arc still apparent in late types. These have their star formation histories weighted more towards current epochs (Gallagher, Hunter, & Tutukov 1984; McGaugh & Bothun 1994). The variation can not be in the absolute amount of star formation, present or past, as this allows for no variation within a given t ypc. Perhaps it is bet ter described by the time scale $\tau \sim$ M./M, the current rate of star formation relative to the total integrated star formation. This in some sense is the inverse of the evolutionary rate, which is rapid for early types and very slow for late types. This would naturally explain the mcmphology-density (Dressler 1980) and surface brightness-density (Bothun et al. 1993; Mo, McGaugh, & Bothun 1994) relations, because galaxies arc expect d to form later and evolve more slowly the more isolated their progenitors (see Mo et al. 994).

3. IMAGES

To give some impression of the galaxies we are discussing, and an idea of the diversity of morphology of LSB disks, we present multicolor CCD images and discuss some interesting individuals. The depth of the CCD images gives rather more information than is available on discovery plates; this can lead to rather different morphological classifications. This is illustrated in Table 1, which compares the types given by the UGC and those determined from the CCD images on the system described by Sandage & Binggeli (1984) as employed by Schombert et al. (1992). Clearly, there is a large uncertainty in type at low surface brightnesses, as classification requires some eyeball interpolation of unseen structures. The UGC classifications have been retained in Figure 1 since the other data. are also photographic, but it is clear that morphological type *per se* is not very meaningful for LSB galaxies.

Surface photometry and colors are discussed by McGaugh & Bothun (1994), as are details of the broad band observations. The Hα observations, described by McGaugh (1992), provide the targets for H II region spectroscopy (McGaugh 1994 b). Like the broad band images, many of the Hα images were obtained with the MDM[1] 1.3 m telescope. Some were obtained with the KPNO 2.1 m telescope with typically longer exposures. Hence these are considerably deeper, a point which should be kept in mind when comparing the images. They are denoted by "2.1 m" in the figure captions.

All images are presented with north up and east to the left. Unless otherwise noted, each image is 2,4' on a side. Most, though not all, were obtained under photometric conditions. Images are scaled to have the same contrast relative to the sky so as to reveal morphology; saturation of the grayscale often happens at quite low surface brightness which varies with the surface brightness of the galaxy.

3.1 *NGC 7757*

'This HSB disk galaxy is included for comparison (Figure 2). An Sc spiral, it is the sort of galaxy most of us probably consider '(typical ." Perhaps contrary to appearances, the exposure time and the signal to noise ratio in the sky is less than in the other images. If displayed in such a way as to make the sky value (rather than the contrast relative to the sky) appear similar, most detail would be lost to saturation.

The disk of this galaxy is consumed by star formation with H II regions tracing a prominent spiral pattern, Despite the much higher star formation rate per unit area, this galaxy is not as blue as most of the LSB galaxies discussed here. Note the change in morphology with filter as the disk becomes progressively smoother in the red, indicative of an old disk population.

3.2 *F415- 3*

This LSB galaxy has a single prominent H II region near its center and amorphous very low surface brightness plumes extending away from the ends of the major axis of the main body (Figure 3). The western plume has several knots which are prominent in

[1] MDM Observatory is operated by the University of Michigan, Dartmouth College, and the Massachusetts Institute of Technology.

the blue filters but which are not obviously H II regions. This may be due to weak $H\alpha$ emission, or a velocity difference which takes the line out of the narrow $H\alpha$ bandpass.

This relatively small (exponential scale length $\alpha = 1.2\ h^{-1}$ kpc) galaxy has a similar appearance in all filters, suggesting a fairly homogeneous population which has not segregated dynamically. The $V - I$ color ($V - I = 0.71$) is remarkably blue. Note the lack of an old red disk. This is a generic property of LSB galaxies, which often lack the diffuse red disks" associated with the old disk component in HSB galaxies. This suggests a population with a giant branch which is underdeveloped due to a late commencement of star formation and a low mean age (McGaugh & Bothun 1994). As indicated by their low surface brightness and the sparse sprinkling of H II regions across the disks, both the past and current star formation rate per unit area is low.

3.3 *F469-2*

This rather large (α = 2,9 h^{-1}kpc) quite LSB ($\mu_0^c = 24.441$? mag arcsec^{-2}) galaxy has nonetheless several prominent H II regions embedded in a chaotic looking disk (Figure 4). 'his galaxy is also quite blue ($U - B = -0.44$, $B - V = 0.43$, $V - I = 0.94$) with a similar morphology in each filter, again suggesting a youthful population. If anything, the disk (as opposed to the spiral pattern) is less prominent in I, contrary to the case in NGC 7757.

3.4 *F530-3*

This galaxy looks fairly normal, with a bulge and a two arm spiral pat tern (Figure 5). Nonetheless, it is much lower surface brightness ($\mu_0^c = 23.85$ mag arcsec^{-2}) than the HSB galaxy to the southeast, which is saturated in these images. This interloper is probably at a different redshift, as it is unusual for large (α = 3.7 h-' kpc in this case) LSB galaxies to have nearby neighbors (Bothun et al. 1993, Mo et al. 1994).

3.5 *F561-1*

A typical size (α = 2.61k kpc) disk, this LSB galaxy has a strong, one arm spiral pattern (Figure 7). Such features are not uncommon in LSB galaxies, suggesting that $m = 1$ spiral modes are possible at low surface densities. Rings and single arms indicate the importance of surface density thresholds (Kennicutt 1989) to the star forming properties of LSB 'disks (van der Hulst et al. 1993).

3.6 *F563-V1*

Despite its dwarf morphology (Figure 8), F563-V1 is not particularly small (α = 1.9 h^{-1} kpc). It nonetheless appears to have a rather homogeneous stellar population. It is also one of the most metal poor extragalactic objects known (McGaugh 1994 b), again suggestive of a young object.

3.7 *F611-1*

This is an otherwise amorphous galaxy with a pair of imbedded knots of star formation (Figure 10). These do not dominate the light as is often the case in star bursting blue compact galaxies (B CGs). While BCGs presumably have LSB progenitors (Tyson & Scalo 1988), the galaxies being discussed here are generally to large and bright to be the progenitor population (though see Taylor, Brinks, & Skillman 1993) which probably involves galaxies which are smaller and perhaps even lower surface brightness when not actively forming stars. Nonetheless, F611 1 is similar to BCGs in that it is also quite metal poor ($Z \lesssim 0.1\ Z_\odot$). The uniformly distributed light, is blue, with $U - B = -0.24$ and $B - V = 0.44$. Though not terribly small ($\alpha = 1.5\ h^{-1}$ kpc), it is quite low surface brightness ($\mu_0^c = 24.5$ mag arcsec^{-2}).

3.8 *UGC 1230*

This normal sized ($\alpha = 3\ h^{-1}$kpc) disk is extremely blue, with $V - I = 0.56$. The galactic reddening is large ($A_B = 0.4$, Burstein & Heiles 1984), so the color depends on the assumed reddening law. However, the observed $V - I = 0.72$ is itself remarkably blue for a composite stellar system. The giant branch in this galaxy must be quite feebly populated, indicating a young mean age.

There is a clear, if diffuse, spiral pattern (Figure 1 2). The spiral arms are not well traced by H II regions as in NGC 7757 though there are a few scattered about. The pair of knots to the south which are prominent in the I-band are also H 11 regions. That faint nebular emission is present in these red clusters indicates that star formation has continued in the vicinity long enough for the the first stars formed in the current episode of star formation to evolve to the red supergiant phase.

3.9 *UGC 12695*

This galaxy has an odd structure, with thick spoke-like structures rather than arms projecting out from the center (Figure 15). These features are present in all filters, indicating a fairly homogeneous stellar population. There are a number of bright H II regions around the edges of the galaxy. In those to the west, a clear trend of color is present in the sense that the southern clusters are bluer than the northern ones, perhaps indicating the propagation of star formation in this direction. The proximity of a very red and blue cluster in the east may indicate a similar situation. Since these star clusters evolve on short (a few x 10^7yr) time scales, and the galaxy as a whole is quite blue ($B - V = 0.37$), star formation could have propagated across the entire galaxy rather recently. The colors are consistent with an age of only a few $\times 10^8$ yr. The gas mass fraction is quite large and the stellar mass to light ratio is low (McGaugh 1992), also consistent with youth. Thus, UGC 12695 seems to be an example of a large ($\alpha \sim 6\ h^{-1}$kpc) disk which has only recently formed. As such it is as reasonable a candidate "protogalaxy" as any, but has the advantage of being close enough to study in detail.

3.10 *F568-6*

The second example of a giant ($\alpha \approx 16\ h^{-1}$kpc) low surface brightness disk, F568-6 (Figure 16) is also known as Malin 2 (Bothun et al. 1990). This is the only LSB galaxy (other than the relatively HSB UGC 5709) known to contain H II regions with metallicities higher than $\sim 0.3 Z_\odot$ (McGaugh 1994 b). A wide range of metallicities are present, suggestive of a steep abundance gradient, though the paucity of H II regions makes this difficult to determine.

3.11 *UGC 6614*

UGC 6614 (Figure 17) is comparable in size to Malin 2 ($\alpha \approx$ 121~-' kpc). A number of other giant disks are also known (Impey & Bothun 1989, Knezek 1993, Sprayberry et al. 1994), but none approach they prototype Malin 1 in terms of scale length ($\alpha \approx 55\, h^{-1}$ kpc; Bothun et al. 1987), The abundance determinations for the H II regions in UGC 6614 arc ambiguous (McGaugh 1994 b), but suggest that unlike the majority of LSB galaxies, it could be quite metal rich, Since only the giant LSB galaxies exhibit high abundances, and also tend to have more prominent bulge components, the disks of these galaxies may have been polluted by metal production in the bulges (Koeppen & Arimoto 1990). The disk of U6614 is very low in surface brightness and extends well out of the field of view. As evident from its red integrated colors, the observed light is dominated almost everywhere by the bulge.

3.12 *F577- VI*

F577-V1 is not well described as an exponential disk, but is comparable in size to a galaxy with $\alpha \approx 3\, h^{-1}$kpc. It is one of the few late type LSB galaxies with a bar (Figure 18) though such features may be common in early type LSB galaxies (de Blok, private communication). Its outer light profile is dominated by a very blue, actively star forming spiral/ring structure.

3.13 *UGC 9024*

This galaxy has a very low surface brightness disk (μ_0^c = 24.71 mag arcsec^{-2}) and a fairly normal looking bulge. Its over all color is quite blue ($B - I$ = 1.18), as is that of the bulge itself ($B - I$ = 1.51). Some hint of spiral structure is apparent in the B image, and is also traced by H II regions in the deep Hα image (Figure 23). The disk is rather large (α = 5.6 h^{-1}kpc), and the presence of the bulge suggests that this may be a transition object between normal sized, bulgeless LSB galaxies and the giant cousins of Malin 1. This galaxy represents a kind of discoverly limit presented by photographic plate technology as its disk is barely discernible on the original plate material.

4. CONCLUSIONS

We have presented multicolor CCD images of a sample of low surface brightness disk galaxies. These exhibit a wide range of morphologic, commensurate with the large area they occupy in the size- surface brightness plane. However, the large physical differences between LSB galaxies are suppressed by morpholgical classification schemes, which tend to assign them only a few vaguely defined types. This suggests that the Hubble sequence is nonlinear in that galaxies with high contrast relative to the sky background arc subject to being more finely typed than those which appear merely as fuzzy blobs on photographic plates. This nonlinear mapping between appearance and underlying physical properties is analogous to that in mapping stellar spectral types to temperature and mass. Hence the differences between early type (Sa, Sb, and Sc) spirals, though real and seemingly large, arc in fact small compared to the entire volume of physical parameter space occupied by disk galaxies.

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FIGURE CAPTIONS

Figure 1. The distribution of disk galaxies in the central surface brightness - exponential scale length plane. Different Hubble types are distinguished with different symbols. The dotted lines of constant luminosity are labeled by the absolute B magnitude of disks with those (μ_0, α). The solid and dashed horizontal lines represent the Freeman (1970) result $\mu_0^c = 21.65 \pm 0.3$; B mag arcsec^{-2}. Note that disks of all sizes exist with surface brightnesses many σ below the Freeman (1970) value, and that there is no obvoious discontinuity in surface brightness over a range of four magnitudes.

Figure 2. NGC 7757. a) U b) B c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$. This HSB spiral is included for comparison purposes. The grayscale is not scaled the same as for tile following LSB images; if it were the entire disk would be saturated.

Figure 3. F415-3. a) U b) B c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$.

Figure 4. F469-2. a) U b) B c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$. The linear streaks result from deferred charge from bright, stars in previous exposures.

Figure 5. F530-3. a) U b) B c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$.

Figure 6. F558-1. a) U b) B c) V d) I e) 2.1 m $H\alpha$ f) continuum subtracted $H\alpha$. Since the $H\alpha$ images were obtained with a larger telescope than for the previous galaxies and filters, they are rather deeper (see text). A fairly normal looking spiral, the broad band images were unfortunately not obtained under photometric conditions so it is difficult to usefully employ the color information. Despite the imperfect continuum subtraction, there are H II regions confirmed by spectroscopy in the southern arm.

Figure 7'. F561-1. a) U b) B c) V d) I e) 2.1 m $H\alpha$ f) continuum subtracted $H\alpha$.

Figure 8. F563-V1. a) U b) B c) V d) I e) 2.1 m $H\alpha$ f) continuum subtracted $H\alpha$. The U band image is not photometric, and this galaxy is rather bluer than seems to be indicated by the low contrast in (a) (de Blok, van der Hulst, & Bothun 1994).

Figure 9. F563-V2. a) U b) B c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$. This galaxy has two H II regions west of the relatively HSB central bar, and a blue, LSB plume to the northwest.

Figure 10. F611-1. a) U b) 13 c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$.

Figure 11. F746-1. a) U b) B c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$. There are a number of star forming regions in this relatively HSB galaxy.

Figure 12. UGC 1230. a) U b) B c) V d) I e) $H\alpha$ f) continuum subtracted $H\alpha$. The various knots are H 11 regions spanning a wide range of intrinsic $H\alpha$ luminosity and broad band color. For example, compare the blue northeastern knots to the red ones due south of them. Though the $H\alpha$ emission of the southern knots is barely discernable in this image, it was easily detected spectroscopically (McGaugh 1992, 1994b).

Figure 13. UGC 5709. a) U b) B c) V d) I e) 2.1 m $H\alpha$ f) continuum subtracted $H\alpha$. This galaxy is intermediate in surface brightness, and displays the same sort of old red disk

seen in HSB galaxies. It is also intermediate in color, being redder than the lower surface brightness disks (McGaugh & Bothun 1994).

Figure 14. UGC 6151. a) U b) B c) V d) I e) 2.1 m Hα f) continuum subtracted Hα. There are quite a few faint H II regions in this irregular LSB spiral.

Figure 15. UGC 12695. a) U b) B c) V d) I e) Hα f) continuum subtracted Hα.

Figure 16. F568-6 = Malin 2, a) U b) B c) V d) I e) 2.1 m Hα. An off band image adequate for continuum subtraction is not available. The B and I images were obtained on a different observing run than the U and V images, the latter being nonphotometric. However, it is useful to intercompare the emission regions visible in the U. The H II regions are predictably bright in this filter, but the oblong structure northwest of the bulge is not. The spectrum of this object is consistent with shock heating (McGaugh 1994b), so it may be a jet associated with the nuclear activity in this giant galaxy (Bothun et al. 1990).

Figure 17. UGC 6614. a) U b) B c) V d) I e) 2.1 m Hα. An off band image adequate for continuum subtraction is not available. The scale of these images is different from the others, being 3.1 rather than 2.4 arcminutes on a side. Spiral structure can be traced to the edge of the frame, and extends well beyond this.

Figure 18. F577-V1. a) U b) B c) V d) I.

Figure 19. F568-1. a) B b) I c) 2.1 m Hα d) continuum subtratced Hα.

Figure 20. F583-5. a) B b) I c) 2.1 m Hα d) continuum subtratced Hα.

Figure 21. F585-3. a) B b) I c) 2.1 m Hα d) continuum subtratced Hα.

Figure 22. UGC 5675. a) B b) I c) 2.1 m Hα d) continuum subtratced Hα.

Figure 23. UGC 9024. a) B b) I c) 2.1 m Hα d) continuum subtratced Hα.